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WEIGHT AND FREQUENCY EFFECT ON SPINAL LOADING IN A BRICKLAYING TASK

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Abstract—In manual materials handling jobs a reduction in the weight of materials often concurs with an increase in handling frequency. The effect of weight and inversely related frequency on spinal load was studied in two bricklaying tasks: building the skin and the floor of a steel ladle. In both tasks five subjects laid bricks of varying weight and frequency (obtained from field observations). The load parameters investigated were peak values and time integrals of the compressive force on the L5–S1 motion segment and stature loss, which is assumed to reflect motion segment creep due to compression. Peak compression was found to increase at higher brick weights. No differences in integrated compression were observed among four out of five combinations of weight and frequency (both in skin and floor building). Laying bricks for a fixed period of 47 min yielded average stature losses of 2.0–3.6 mm. Differences in stature loss among weight–frequency conditions were not significant. In conclusion, at lower weights peak loads decrease, but the benefit of this should be doubted because the frequency of exposure to these peak loads was found to increase. Moreover, this increase was such that no effects were found on spinal load estimates that incorporate both magnitude and time aspects of the load, like time-integrated compression and stature loss. Copyright © 1996 Elsevier Science Ltd.

Keywords: Spinal compression; Spinal shrinkage; Manual materials handling; Biomechanics; Ergonomics.

INTRODUCTION

The high prevalence of low back pain (LBP) in manual materials handling jobs is well known. As regards the underlying etiology, it is generally believed that the handling of heavy weights imposes a mechanical load on low back structures, which exceeds their strength. Mechanical damage of structures of the lumbar spine plays a major role in the development of many low back complaints (Bogduk and Twomey, 1987). Much biomechanical effort has been directed towards the development of methods to determine the magnitude of the load on, and the strength of, spinal motion segments (Hansson *et al.*, 1980; McGill and Norman, 1986). A main ergonomic strategy to reduce LBP prevalence has been to reduce the peak mechanical loads in occupational tasks by redesigning the work or work place.

A reduction of the mechanical load in manual materials handling could be achieved by a reduction of the materials' weight. The weight, however, is often inversely related to the handling frequency in occupational field settings. As the weight of the materials decreases, a higher frequency is often preferred or obliged to attain similar productivity levels. The effect of this feature on the metabolic energetic load on workers has been recognized for a long time. Hamilton and Chase (1969) found that at

a given productivity, it is energetically preferable to handle higher weights at lower frequencies than lower weights at higher frequencies.

With respect to mechanical load, it is clear that a combination of lower weights and higher frequencies yields lower peak loads but a higher frequency of exposure. In a comprehensive evaluation of spinal load, both factors should be incorporated. *In vitro* research showed that motion segment damage may arise, not only from a single maximal compressive force, but also from cyclic loading protocols at submaximal force level (Brickman *et al.*, 1988; Hansson *et al.*, 1987; Liu *et al.*, 1983). In that case the occurrence of failure largely depends on the number of loading cycles, while the number of cycles at which structures fail is related to the level of the stress applied (Hansson *et al.*, 1987). This shows the importance of time of exposure to the load beside the load's magnitude. In ergonomics however, time aspects are greatly ignored in biomechanical evaluations, which is in large contrast to the interest in the magnitude of peak spinal loads (van Dieën and Oude Vrielink, 1994).

It was investigated in the present study whether beneficial effects of lighter weights in terms of spinal load are neglected by the effects of the accessory higher handling frequency in the manual task of brick laying. Therefore, the spinal load was investigated under varying conditions of brick weight and handling frequency. The spinal load was evaluated on the basis of several parameters. The compressive force on the L5–S1 motion segment was estimated by use of a dynamic biomechanical model. From the instantaneous force curves, peak and time-integrated values were obtained. In addition, the loss of stature was measured after a fixed period of laying bricks.

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Stature loss reflects the creep of motion segments caused by compression and has been shown to be affected by the magnitude and temporal aspects of the load (e.g. Helander and Quance, 1990; Leskinen and Stålhammar, 1990). Hence, this approach creates, like the time-integral of the compressive force, the possibility of quantifying the integrated effect of brick weight and handling frequency.

MATERIALS AND METHODS

The experiments took place in a steel industry at the department, where steel ladles are built by laying bricks. Two activities were investigated: laying bricks in the skin and in the floor of the ladle. Professional bricklayers performed the activities under varying combinations of brick weight and bricklaying frequency. For both activities, first, stature loss was determined from measurements of stature before and immediately after a fixed period of bricklaying. Secondly, various movement phases of a bricklaying cycle were simulated by the subjects to estimate the time-history of the spinal compressive force in each cycle.

Ten healthy male professional bricklayers (age, 33.2 ± 10.1 yr; body mass, 82.2 ± 8.3 kg; stature, 1.81 ± 0.07) volunteered in the experiments. Five of them participated in the experiments on building the skin, and five participated in the experiments on building the floor. No significant differences between both groups were observed regarding stature, body mass and age. Prior to the experiments the subjects gave their informed consent.

The subjects first performed the bricklaying tasks to determine effects on stature loss. These were performed in a half-round wooden construction, which represented half the inner side of a ladle. At the center of this construction, the bricks to be used were placed on a pallet. Care was taken to imitate the real working situation as closely as possible. To build the skin or the floor of the construction, bricks were picked up from the pallet, held and greased by mortar and positioned. In building the skin, bricks were laid starting at a level of 0.42 m. In building the floor the bricks were laid down at the level the worker was standing on. The heaviest brick applied for the floor proved to be too heavy to hold in the hands during greasing for four of the five subjects. These subjects used a supporting shelf (on waist height level) on which the brick was laid for greasing. Subjects were told to lay the bricks at a frequency that was indicated by an auditory signal from a metronome. The total duration of the bricklaying activities was 47 min: two periods of 23.5 min of bricklaying interspread by a 3 min resting break. Before and immediately after the task, stature was measured as described in the next paragraph.

Next, subjects participated in the second experiment, in which the different movement phases in a bricklaying cycle were imitated (from which spinal compression was estimated). The movements involved were restricted to the sagittal plane in order to be able to apply a two-dimensional biomechanical model. This yielded the following movement phases; phase 1, moving a brick from

a height level of 0.70 m to waist level at 0.10 m in front of the body by two hands; phase 2, holding a brick in two hands at waist level 0.10 m in front of the body; phase 3, lowering the brick down to a height of 0.42 m (in skin building) or ground level (in floor building) by two hands; phase 4, straightening to an upright standing position without a brick in the hands; phase 5, standing upright without a brick.

Each subject was invited on five consecutive days. Each day, he followed the same protocol, but the bricks varied in size and weight. Also, the bricklaying frequency (in the 47 min task) varied among the different types of brick. The frequency applied was obtained from the bricklaying frequencies observed for the various bricks in real ladle building. In Table 1 it can be seen that an increasing brick weight concurs with a decreasing frequency. However, the productivity in terms of total mass of bricks per min is not constant among the various weight-frequency conditions. The sequence of the five conditions was fully balanced over the five subjects to avoid order effects.

To measure stature loss, the apparatus described by van Dieën *et al.* (1994) was used. By analogy with the stadiometers described by Corlett and Eklund (1977) and Althoff *et al.* (1992) the apparatus was equipped with several facilities to help the subjects to reproduce an identical posture in each measurement. Four force plates were mounted on the base plate to measure the weight distribution over heels and soles and left and right foot. This distribution was visually fed back on a computer screen to help the subjects to reproduce it in subsequent measurements. Similarly, the pressure against the back rest at three positions (spinous process L4, spinous process of C4, the back of the head) were fed back and had to be reproduced. Furthermore, the inclination of the head in the sagittal plane was controlled by instructing the subjects to align a horizontal marker on their forehead with a line on a mirror positioned 3 m in front of them. Finally, the apparatus was tilted backwards 12° to minimize muscle activity. Measurements of stature were taken by lowering a light round plate with cylindrical pins on the edge connected to a displacement transducer on the subject's head. The output of the transducer was

Table 1. The bricks used and the bricklaying frequencies in the activities of laying bricks in the skin and laying bricks in the floor.

Activity	Brick No.	Weight (kg)	Frequency (bricks min ⁻¹)
Laying bricks in the skin	1	1.5	6.0
	2	3.2	5.0
	3	4.6	4.0
	4	6.3	3.0
	5	8.1	2.0
Laying bricks in the floor	1	3.6	5.0
	2	5.2	4.0
	3	7.5	3.5
	4	9.8	3.0
	5	16.1	2.0

digitized. As stature varies during the day, the subjects were measured each day at the same time. They were asked to limit variations in their pattern of activity among the five experimental days prior to the time of the experiment. Additionally, for standardization purposes, the subject were asked to lie down in Fowler's position for 20 min prior to the experiments.

Prior to the experiments, a training protocol devised by van Dieën and Toussaint (1993) was used, in which 22 bricklayers were familiarized in reproducing stable body postures on the equipment. The protocol consisted of 20 or more measurements. In between the measurements the subjects stepped off the measuring device. In the series of measurements standard deviations were calculated for measurements 1–10, 2–11, 3–13, etc. The training ended when ten successive standard deviations calculated this way were below 1.0 mm. The ten subjects showing the lowest standard deviations at the end were invited to participate in the actual experiments.

In the actual experiment, five control measurements were taken for checking the positions of the adjustable supports and familiarizing the subjects with the instrumentation again. Next, five measurements were performed before and immediately after the 47 min period of brick laying. Stature loss was determined from the difference in the median values.

The compressive forces on the L5–S1 intervertebral disc were estimated, on the basis of movement analysis, individual segment anthropometry and a dynamic biomechanical model.

To analyze movements, light reflective markers were placed on the subject's right side at relevant anatomical positions: the lateral femoral epicondyle, the uppermost margin of the greater trochanter, the intervertebral disk between the fifth lumbar and first sacral vertebra (L5–S1) from a lateral view (according to de Looze *et al.*, 1992), the spinous process of the first thoracic (T1) vertebra, anterior to the ear canal, the acromion, the lateral humeral epicondyle, the distal end of the ulnar styloid process and the distal end of the third metacarpal. The instantaneous positions of these markers during movements were recorded by use of a motion analysis system (VICON, Oxford Metrics) at a rate of 60 frames s^{-1} . The markers' coordinates in the sagittal plane were low pass filtered (effective cut-off frequency of 5 Hz, zero phase lag, 2nd order Butterworth). From the filtered body marker positions a dynamic linked segment model was constructed comprising seven segments: upper legs, pelvis, trunk, head, upper arms, fore arms and a hands/load segment (de Looze *et al.*, 1992).

Prior to the experiments, stature, total body mass and body segment lengths were measured. On the basis of these measurements and on the basis of tables (Plagenhoef, 1983) the segmental masses, the moments of inertia and the relative positions of the centers of gravity were estimated for each individual. With respect to the pelvis and trunk, data from Liu *et al.* (1971) on the segment parameters of lumbar vertebral segments were scaled to subject length and used to recalculate the trunk and pelvis data from Plagenhoef in order to obtain the seg-

mentation plane between the pelvis and the trunk at the lumbo-sacral joint.

On the basis of the kinematic data, anthropometrical data and brick weights the instantaneous net joint moments and joint reaction forces at the wrist, elbow, shoulder and finally at L5–S1 were estimated by means of an inverse dynamical analysis (Elftman, 1939). Next, compressive and shear forces were estimated assuming that the L5–S1 moment was generated by a single extensor muscle acting at a distance of 61 mm posterior to the centroid of the disk (McGill and Norman, 1986). A possible effect of the abdominal pressure to support an extending lumbar moment, which has been seriously questioned in the literature (e.g. Nachemson *et al.*, 1986), was neglected in the calculations. As the validity of the absolute values of spinal compression might be questioned because of these simplifying assumptions, it should be noted that the conclusions to be drawn from this study will be of a comparative nature only.

In each movement phase studied, peak and time-integrated values were obtained from the instantaneous spinal compression curves. Finally, an estimation was made of the time-integral of spinal compression (IC) over the entire period of bricklaying in the 47 min task by taking the duration of each movement phase as observed in the 47 min bricklaying task as well as the bricklaying frequency into consideration, according to

$$IC = f \cdot 47 \sum_{\text{phase } 1}^n (\int F_p dt) \quad (1)$$

in which IC = time-integral of spinal compression in the 47 min task in Ns, f = brick laying frequency in bricks min^{-1} , F_p = the spinal compressive force in phase p in N.

Finally, the significance of effects of the combinations of brick weight and laying frequency on peak and integrated compression and stature loss was tested by an analysis of variance (ANOVA) with repeated measures and post-hoc comparisons (Tukey-HSD) at a significance level of 0.05.

RESULTS

The estimated time-history of the compressive force for one of the subjects is presented in Fig. 1. The instantaneous compressive force over a period of 1 min for each brick applied in building the ladle's skin is presented. Within each bricklaying cycle the subsequent phases of movement can be discerned: moving the brick closer to the body (first peak), holding the brick (first constant level), bending forward to lay down the brick and straightening the back (second peak) and standing in upright position without a brick in the hands (second constant level). For the figure the different loading patterns for the different bricks become clear. As brick weight increases from the top to the bottom panel, the force level rises in the phases in which the brick is in the hands and the number of cycles per minute decreases. It can also be seen that the periods of standing without a brick ('resting period') get relatively longer as the brick

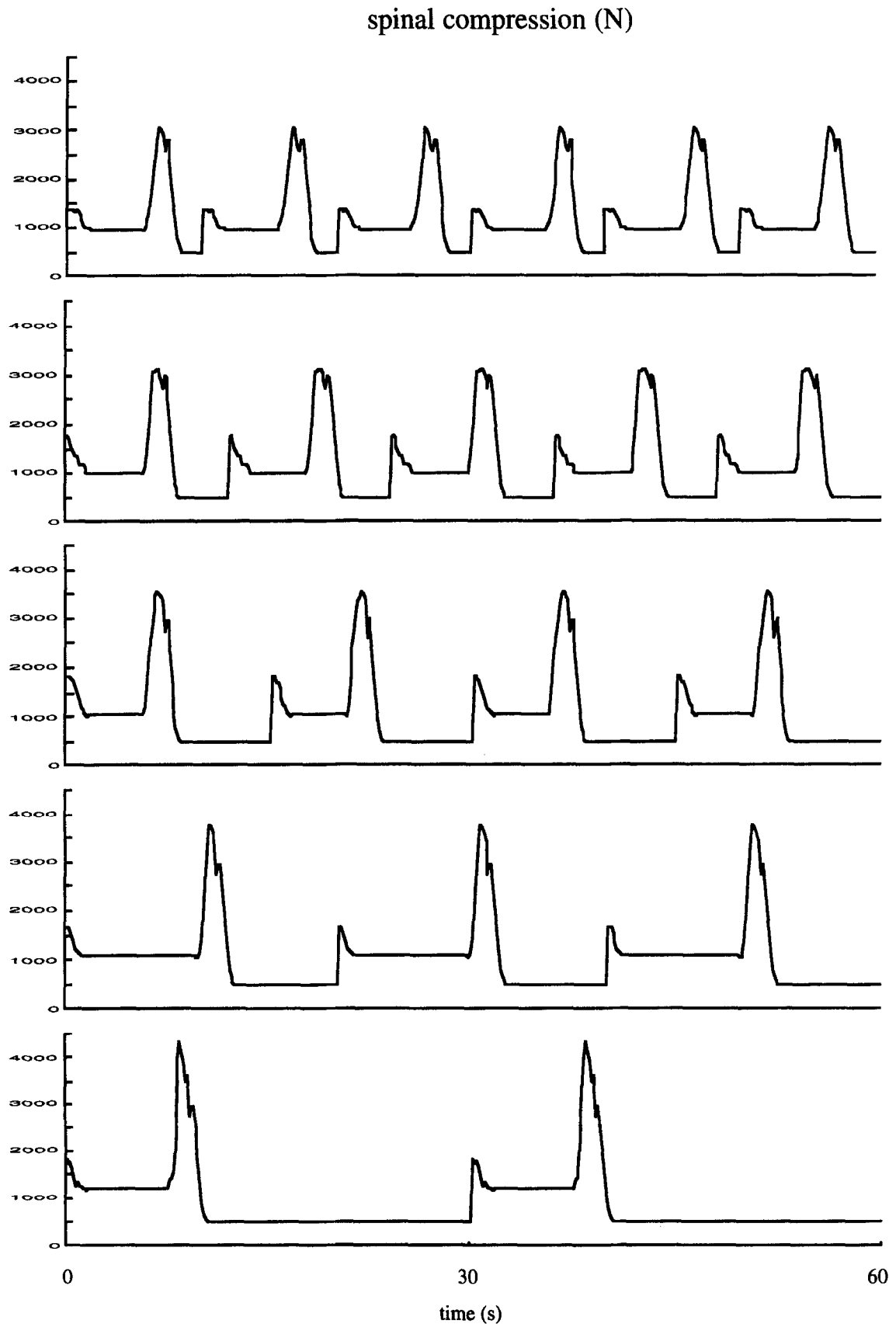


Fig. 1. Time-history curves of spinal compression in building the skin for the five brick weight-handling frequency conditions for one of the subjects. From the upper to the lower panel, brick weight increases and handling frequency decreases.

weight increases, which was a common finding in all subjects.

The average results (and standard deviations) on the activity of building the skin are presented in Fig. 2. The upper two panels show the peak compression values and the estimated time integrals of spinal compression over the entire testing period. The tendency of increasing peak values at increasing brick weights in the various phases of movement was found to be significant. Due to the inversely related frequency which is incorporated in the

calculation of the integrated compression (IC), the effects on IC are very dissimilar compared to the effect on peak values. The IC for brick 5 (highest weight, lowest frequency) is significantly lower compared to the IC for bricks 1, 2 and 3, while no significant differences are observed among bricks 1–4. The lower panel shows the results on stature loss. Laying bricks for 47 min resulted in an average loss of stature varying from 1.7 to 2.4 mm among the five bricks. However, the differences in stature loss among the various bricks were not significant. The

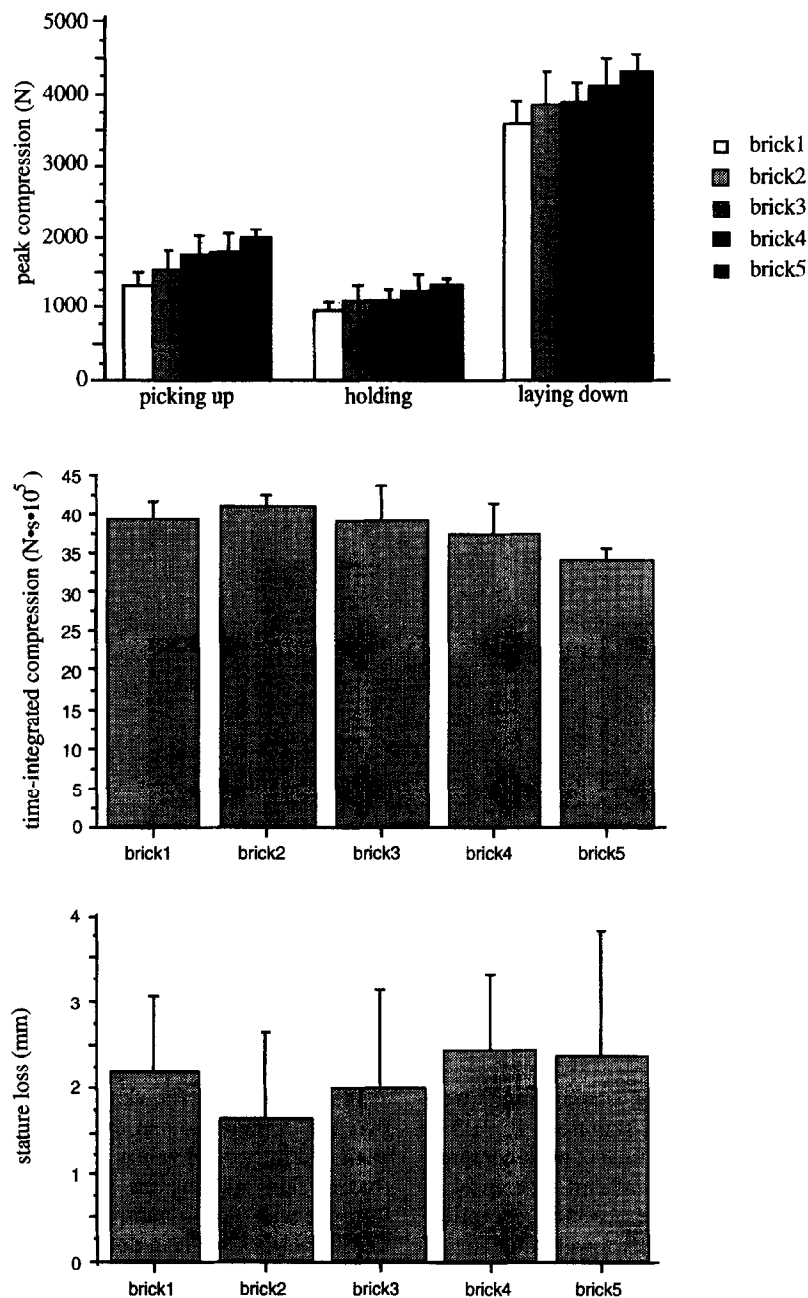


Fig. 2. Results on building the skin. Means and standard deviations of peak compression, time-integrated compression over a period of 47 min of bricklaying and stature loss after 47 min bricklaying

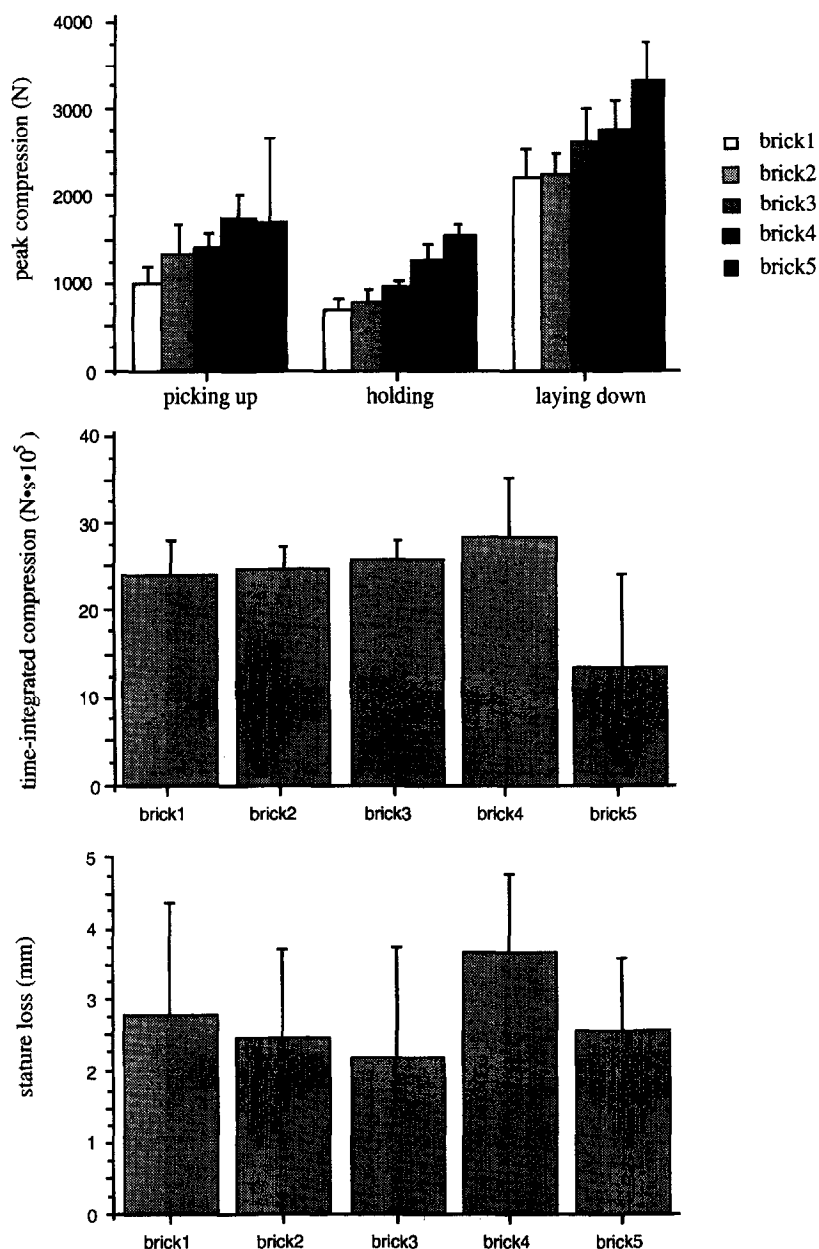


Fig. 3. Results on building the floor. Means and standard deviations of peak compression, time-integrated compression over a period of 47 min of bricklaying and structure loss after 47 min bricklaying

intersubject variation in stature loss was quite large, standard deviations for the various bricks ranged from 0.8 to 1.4 mm.

In building the floor of the ladle, similar results were found as compared to building the skin (see Fig. 3). The effect of brick weight on the magnitude of peak compression again was significant. No significant differences in IC among the various bricks were observed, except for brick 5 which showed a significantly lower value for IC than bricks 3 and 4. This seems to be the result of the use of the supporting shelf in the holding and greasing phase by four of the five subjects. The use of this shelf however did not become apparent in the results on the loss of

stature. No significant differences were found among the various bricks. The average stature loss was in a range from 2.1 to 3.6 mm among the five bricks.

When comparing the 'skin and floor results', it appears that the compression in skin building reached higher peak and integrated values. This is explained by the fact that in skin building the worker keeps some distance from the wall (not to bump his head) and bends forward to lower bricks, while in floor building the trunk is more erect and bricks are lowered close to the body. Hence, the trunk and brick position in skin building creates larger lumbar moments. This did not result in more stature loss. Instead, there is a tendency (not significant) to less stature

loss in building the skin. This might be due to minor differences in task performance between the two experiments from which stature loss (47 min task) and compression (simulation of phases) were derived. It should also be stressed that the subjects in skin and floor building were different and that stature loss is greatly affected by subject characteristics. Care should thus be taken in skin vs floor comparisons.

DISCUSSION

Weight-frequency effects

The phenomenon of inversely related weights and frequencies is not uncommon in manual materials handling. Its impact on spinal loading was addressed in this study. It was found for two bricklaying tasks that the values of peak compression increased at higher weights. Considering time-integrated compression and stature loss however, it appeared that the effect of the increase in brick weight was generally negated by the decrease in handling frequency.

In the study the frequencies applied were obtained from the real working situation. As a result the produc-

tivity in kg min^{-1} was not constant among conditions (Fig. 4). Mainly in floor building an increase in productivity at increasing weight was apparent. Even despite this, the above-mentioned compensation of weight by frequency effects was observed. A correction for productivity on the integrated compression and stature loss was found not to influence the statistical results reported.

The study indicates that a reduction in brick weight is not per definition advantageous. Considering relatively simple estimates of spinal load that incorporate time aspects, it appears that effects of weight are compensated by frequency effects. It cannot be stated from this study whether a lighter weight at the cost of a higher frequency would be preferable or vice versa. While the values for peak compression favors a combination of lower weights and higher frequencies, the frequency of exposure to these forces favors the opposite and finally, the integrated compression and stature loss did not speak in favor of the one or the other. Moreover, the relative impact of the parameters on the risks of LBP which could only be established from longitudinal epidemiological research, is unclear.

Ever since Chaffin and Park (1973) established a relationship between the level of peak spinal compression in

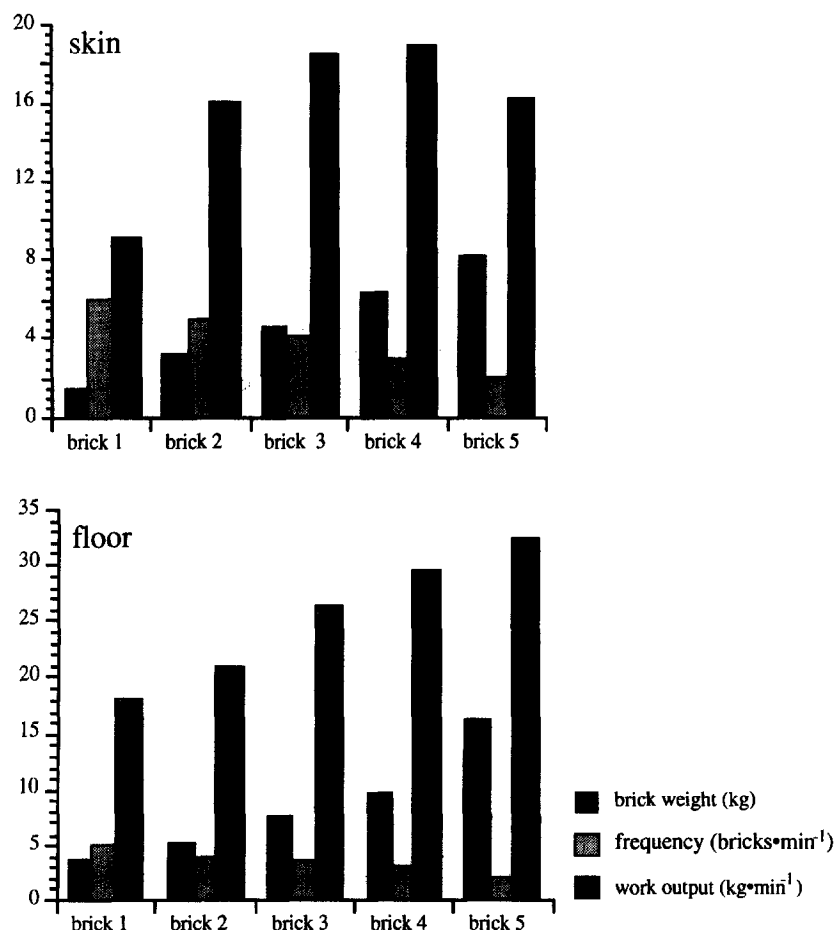


Fig. 4. Resulting work output in the various combinations of brick weight and handling frequency in building the skin and floor of the ladle.

occupational lifts and LBP incidence, much ergonomic effort has been directed towards reducing peak loads or eliminating peak loading events. It appears in practice however that workers who are exposed to lifting relatively low weights or frequent bending without a load also show increased risks for LBP (Berquist-Ullman and Larsson, 1977; Frymoyer *et al.*, 1980; Magora, 1970). These observations are in line with *in vitro* results that show that spinal damage also occurs in cyclic submaximal loading (Brinckman *et al.*, 1988; Hansson *et al.*, 1987; Liu *et al.*, 1983). Hansson *et al.* (1987) found that the number of cycles at which failure (end-plate fractures) was observed was inversely related to the compressive stress applied. Lafferty *et al.* (1977) found a similar relationship for the bending stress and the number of cycles to damage of posterior elements of vertebrae. Temporal aspects, like time of exposure, are thus of importance beside the magnitude of the load. These findings agree with the notion that biologic tissue is of a visco-elastic nature and cyclic loading would result in residual deformation and cumulative fatigue reducing the threshold stress at which tissues fail (Burstein and Frankel, 1968).

Hence, for occupations in which the spinal load is cyclic and submaximal (like in bricklaying), the magnitude of peak loads alone is not a good criterion to evaluate risks for damage as time aspects are ignored. Therefore other criteria should be considered, although until now clear relationships for other criteria to LBP incidence have not been established.

Time-integrated compression and stature loss

In the integral of spinal compression over time, magnitude and temporal aspects are united. In a recent study a measure of time-integrated spinal load, incorporating the magnitude and the time of exposure to spinal compression in nursing tasks, was found to be positively related to LBP prevalence (Kumar, 1990). Major conclusions cannot be drawn from this study however as the effects of peak load, load duration or load frequency were not separated out. From a theoretical point of view the time integral of force as a risk-determining factor can be criticized. It assumes a linear relationship between time of exposure and risk for damage, which does not agree with the visco-elastic behavior of the structures involved.

In the direct measurement of stature loss this behavior is accounted for, while a link between height loss and pathologic changes seems plausible from *in vitro* investigations (van Dieën and Toussaint, 1993). Stature loss can be traced to height loss of the spine as no other structure can accommodate height changes of the magnitude involved (Broberg, 1993). Spinal height loss is regarded as the result of spinal compression over time. The dependency of stature loss on the magnitude of the load in terms of the weight lifted has been demonstrated on static axial loading and dynamic lifting (Althoff *et al.*, 1992; Corlett and Eklund, 1986; Tyrell *et al.*, 1985; Vincent *et al.*, 1987). *In vitro* and *in vivo* research illustrate the time-dependent character of height loss of spinal motion segments and stature (Helander and Quance, 1990; Kazarian, 1975; Leskinen and Stålhammar, 1990).

From an extensive review article on stature loss measurement, it was concluded that the method differentiates adequately between loads differing in magnitude and that the effects of load duration can be easily determined (van Dieën and Toussaint, 1993).

In the present study, we found average stature losses from 1.7 to 3.6 mm. Generally, the values reported from lifting studies are higher, namely in the range of 3.9–6.9 mm (van Dieën *et al.*, 1994; Stålhammar *et al.*, 1992; Tyrell *et al.*, 1985). This can be explained by the lower weights and frequencies applied in the present study. We also found a large intersubject variation in stature loss, which agrees with previous reports. This might be due to the variation in age (affecting the affinity for water of the discus), the disc height or area and the grade of disc degeneration (Michel and Helander, 1994). Also the time of day of the experiments, standardized within but not among subjects, is likely to be of influence.

No differences in stature loss were found among the weight and frequency conditions which was attributed before to a compensation of weight effects by frequency effects. It cannot be totally excluded however that in this relatively small group of subjects intersubject variations would have masked any variation in stature loss due to weight and frequency, nor that the method's discriminative power had been sufficient in the specific case of evaluating conditions of varying weight and frequency.

Concluding remarks

From the present study it was concluded that it is not clear that a reduction in brick weight implies a reduction of the spinal load. In practice as the weight becomes lighter, the handling frequency increases, which means lower peak loads but a higher frequency of exposure to these loads. Moreover, no effect of a lower weight (in combination with a higher frequency) was found on load measures that incorporate the magnitude and the time aspects of the load, like time-integrated compression and stature loss. The importance of incorporating time aspects (beside load magnitude) in risk assessment has been demonstrated in *in vitro* and epidemiologic research.

In this study the LBP problem was addressed by considering the mechanical load on and the resultant height loss of the spinal motion segment. Certainly, this is not the only structure where the origin of LBP might be located. In this respect it should be noted that many forms of musculoskeletal injury throughout the body, classified under terms like repetitive strain injury or cumulative trauma disorder, appear to arise from low-intensity repetitive work. It thus seems that, also for structures other than the spinal motion segment, the incorporation of the time aspects of the load is of importance in risk evaluations.

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